What is geothermal energy?

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Heat is a form of energy and *geothermal energy* is literally the heat contained within the Earth that generates geological phenomena on a planetary scale. "Geothermal energy" is often used nowadays, however, to indicate that part of the Earth's heat that can, or could, be recovered and exploited by man, and it is in this sense that we will use the term from now on.

Brief geothermal history

The presence of volcanoes, hot springs, and other thermal phenomena must have led our ancestors to surmise that parts of the interior of the Earth were hot. However, it was not until a period between the sixteenth and seventeenth century, when the first mines were excavated to a few hundred metres below ground level, that man deduced, from simple physical sensations, that the Earth's temperature increased with depth.

The first measurements by thermometer were probably performed in 1740, in a mine near Belfort, in France (Bullard, 1965). By 1870 modern scientific methods were being used to study the thermal regime of the Earth, but it was not until the twentieth century, and the discovery of the role played by *radiogenic heat*, that we could fully comprehend such phenomena as heat balance and the Earth's thermal history. All modern thermal models of the Earth, in fact, must take into account the heat continually generated by the decay of the long-lived radioactive isotopes of uranium (U^{238}, U^{235}), thorium (Th^{232}) and potassium (K^{40}), which are present in the Earth (Lubimova, 1968). Added to radiogenic heat, in uncertain proportions, are other potential sources of heat such as the primordial energy of planetary accretion. Realistic theories on these models were not available until the 1980s, when it was demonstrated that there was no equilibrium between the radiogenic heat generated in the Earth's interior and the heat dissipated into space from the Earth, and that our planet is slowly cooling down.

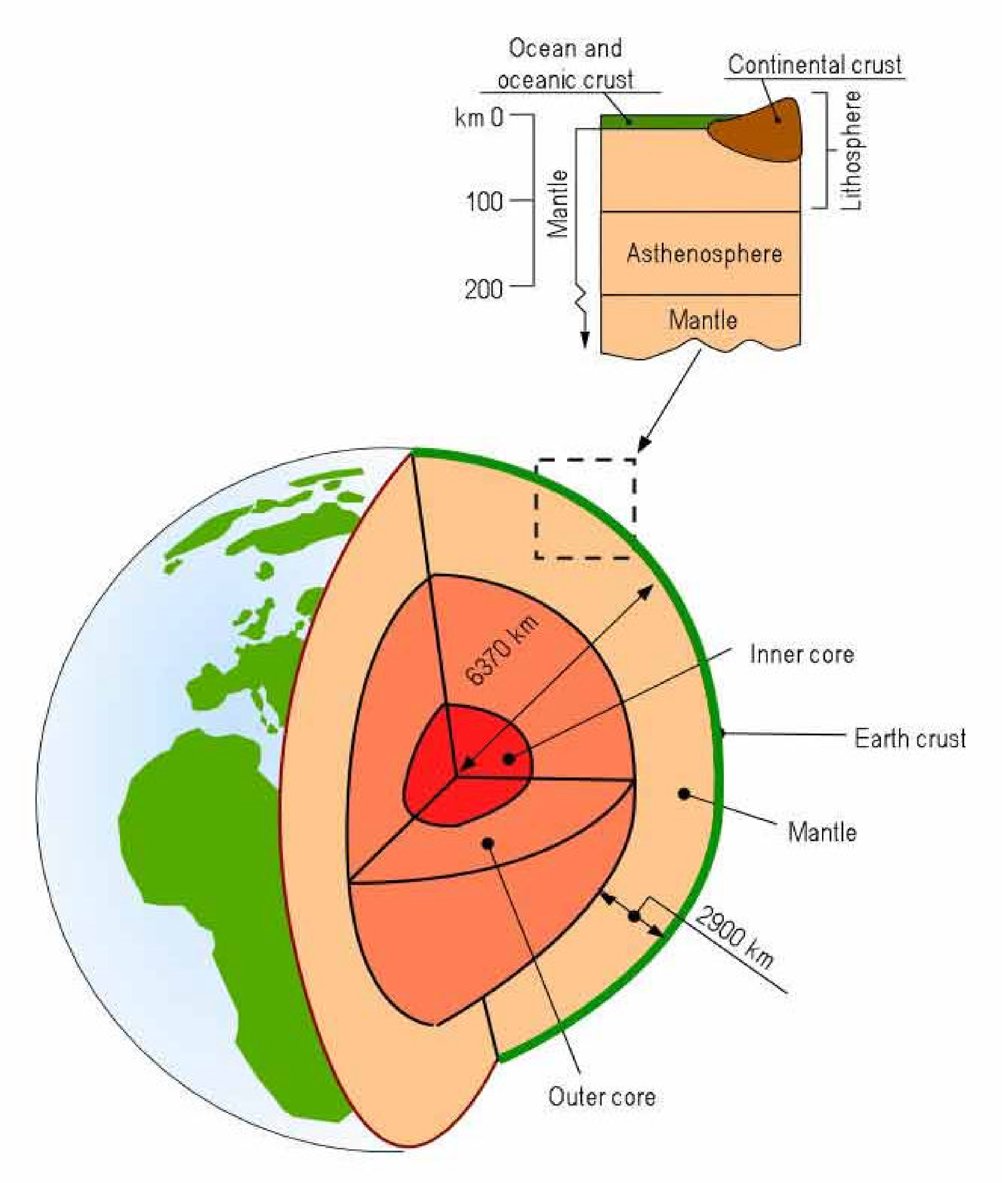

Figure 1
The Earth's crust, mantle, and core. Top right: a section through the crust and the uppermost mantle.

The cooling process is, however, very slow. The temperature of the mantle (Figure 1) has decreased no more than 300-350°C in three billion years, remaining at about 4000°C at its base. Estimates from more than twenty years ago gave the total heat content of the Earth, reckoned above an assumed average surface temperature of 15 °C, in the order of 12.6×10^{24} MJ, and that of the crust in the order of 5.4×10^{21} MJ (Armstead, 1983). The thermal energy of the Earth is therefore immense, but only a fraction can be utilized by man. So far our utilization of this energy has been limited to areas in which geological conditions permit a carrier (water in the liquid phase or steam) to "transfer" the heat from deep hot zones to or near the surface, thus giving rise to geothermal resources, but innovative techniques in the near future may offer new perspectives in this sector.

There are examples in many areas of life of practical applications preceding scientific research and technological developments, and the geothermal sector is no exception. In the early part of the nineteenth century the geothermal fluids were already being exploited for their energy content. A chemical industry was set up in that period in Italy, in the zone now known as Larderello, to extract boric acid from the hot waters issuing naturally or from specially drilled shallow boreholes. The boric acid was obtained by evaporating the hot fluids in iron boilers, using the wood from nearby forests as fuel. In 1827 Francesco Larderel, founder of this industry, developed a system for utilizing the heat of the boric fluids in the evaporation process, rather than burning wood from the rapidly depleting forests. Exploitation of the natural steam for its mechanical energy began at much the same time. The geothermal steam was used to raise liquids in primitive gas lifts and later in reciprocating and centrifugal pumps and winches, all of which were connected with drilling activity or in the local boric acid industry. Between 1850 and 1875 the factory at Larderello held the monopoly in Europe for boric acid production. Between 1910 and 1940 the low pressure steam in this area of Tuscany was brought into use to heat the industrial and residential buildings and greenhouses. In 1928 Iceland, another pioneer in the utilization of geothermal energy, also began exploiting its geothermal fluids (mainly hot waters) for domestic heating.

The first attempt at generating electricity from geothermal steam was made at Larderello in 1904. The success of this experiment indicated the industrial value of geothermal energy and marked the beginning of a form of exploitation that was to develop significantly from then on. Electricity generation at Larderello was a commercial success. By 1942 the installed geothermoelectric capacity had reached 127,650 $kW_{e.}$ The example set by Italy was followed by several countries. The first geothermal wells in Japan were drilled at Beppu in 1919 and in the USA at The Geysers, California, in 1921. In 1958 a small geothermal power plant began operating in New Zealand, in 1959 in Mexico, in 1960 in the USA, and in many other countries in the years to follow.

Present status of geothermal utilization

After the Second World War many countries were attracted by geothermal energy, considering it to be economically competitive with other forms of energy. It did not have to be imported, and, in some cases, it was the only energy source available locally. The countries that utilize geothermal energy to *generate electricity* are listed in Table 1, which gives the installed geothermal electric capacity worldwide in 1995 (a world total of 6833 MW_e) and in the year 2000 (7974 MW_e) (Huttrer, 2001).

Geothermal power can play a fairly significant role in the energy balance of some areas, and of the developing countries in particular, as can be inferred from the data reported in Table 2, which shows the percentage of geothermal power with respect to total electric power installed in some of these countries, relative to 1996.

As regards *non-electric applications* of geothermal energy, Table 3 gives the installed capacity (15,145 MW_t) and energy use (190,699 TJ/yr) worldwide referred to the year 2000. There are now 58 countries reporting direct uses, compared to 28 in 1995 and 24 in 1985. The data reported in this Table are difficult to collect and interpret, and should be used with caution. The most common non-electric use worldwide (in terms of installed capacity) is heat pumps (34.80%), followed by bathing (26.20%), space heating (21.62%), greenhouses (8.22%), aquaculture (3.93%), and industrial processes (3.13%) (Lund and Freeston, 2001).

NATURE OF GEOTHERMAL RESOURCES

The Earth's thermal engine

The *geothermal gradient* expresses the increase in temperature with depth in the Earth's crust. Down to the depths accessible by drilling with modern technology, the average geothermal gradient is about 2.5-3 °C/100 m. For example, if the temperature within the first few metres below ground-level, which on average corresponds to the mean annual temperature of the external air, is 15 °C, then we can reasonably assume that the temperature will be about 65°-75 °C at 2000 m depth, 90°-105 °C at 3000 m and so on for a further few thousand metres. There are, however, vast areas in which the geothermal gradient is far from the average value. In areas in which the deep rock basement has undergone rapid sinking, and the basin is filled with geologically "very young" sediments, the geothermal gradient may be lower than 1 °C/100 m. On the other hand, in some "geothermal areas" the gradient is even higher than ten times the average value.

The temperature increase with depth, as well as volcanoes, geysers, hot springs etc., are in a sense the visible or tangible expression of the heat in the interior of the Earth, but this heat also engenders other phenomena that are less discernable by man, but of such magnitude that the Earth has been compared to an immense "thermal engine". We will try to describe these phenomena, referred to collectively as the *plate tectonics* theory, in simple terms, and their relationship with geothermal resources.

Our planet consists of a *crust*, which reaches a thickness of about 20-65 km in continental areas and about 5-6 km in oceanic areas, a *mantle*, which is roughly 2900 km thick, and a *core*, about 3470 km in radius (Figure 1). The physical and chemical characteristics of the crust, mantle and core vary from the surface of the Earth to its centre. The outermost shell of the Earth, known as the *lithosphere*, is made up of the crust and the upper layer of the mantle. Ranging in thickness from less than 80 km in oceanic zones to over 200 km in continental areas, the lithosphere behaves as a rigid body. Below the lithosphere is the zone known as the *asthenosphere*, 200-300 km in thickness, and of a "less rigid" or "more plastic" behaviour. In other words, on a geological scale, where time is measured in millions of years, this part of the Earth behaves in much the same way as a fluid in certain processes.

Because of the difference in temperature between the different parts of the asthenosphere, convective movements and, possibly, convective cells were formed some tens of millions of years ago. Their extremely slow movement (a few centimetres per year) is maintained by the heat produced continually by the decay of the radioactive elements and the heat coming from the deepest parts of the Earth. Immense volumes of deep, hotter rocks, less dense and lighter than the surrounding material, rise with these movements towards the surface, while the colder, denser and heavier rocks near the surface tend to sink, re-heat and rise to the surface once again, very similar to what happens to water boiling in a pot or kettle.

In zones where the lithosphere is thinner, and especially in oceanic areas, the lithosphere is pushed upwards and broken by the very hot, partly molten material ascending from the asthenosphere, in correspondence to the ascending branch of convective cells. It is this mechanism that created and still creates the *spreading ridges* that extend for more than 60,000 km beneath the oceans, emerging in some places (Azores, Iceland) and even creeping between continents, as in the Red Sea. A relatively tiny fraction of the molten rocks upwelling from the asthenosphere emerges from the crests of these ridges and, in contact with the seawater, solidifies to form a new oceanic crust. Most of the material rising from the asthenosphere, however, divides into two branches that flow in opposite directions beneath the lithosphere. The continual generation of new crust and the pull of these two branches in opposite directions has caused the ocean beds on either side of the ridges to drift apart at a rate of a few centimetres per year. Consequently, the area of the ocean beds (the oceanic lithosphere) tends to increase. The ridges are cut perpendicularly by enormous fractures, in some cases a few thousand kilometres in length, called *transform faults.* These phenomena lead to a simple observation: since there is apparently no increase in the Earth's surface with time, the formation of new lithosphere along the ridges and the spreading of the ocean beds must be accompanied by a comparable shrinkage of the lithosphere in other parts of the globe. This is indeed what happens in *subduction zones*, the largest of which are indicated by huge ocean trenches, such as those extending along the western margin of the Pacific Ocean and the western coast of South America. In the subduction zones the lithosphere folds downwards, plunges under the adjacent lithosphere and re-descends to the very hot deep zones, where it is "digested" by the mantle and the cycle begins all over again. Part of the lithospheric material returns to a molten state and may rise to the surface again through fractures in the crust. As a consequence, *magmatic arcs* with numerous volcanoes are formed parallel to the trenches, on the opposite side to that of the ridges. Where the trenches are located in the ocean, as in the Western Pacific, these magmatic arcs consist of chains of volcanic islands; where the trenches run along the margins of continents the arcs consist of chains of mountains with numerous volcanoes, such as the Andes. Figure 2 illustrates the phenomena we have just described.

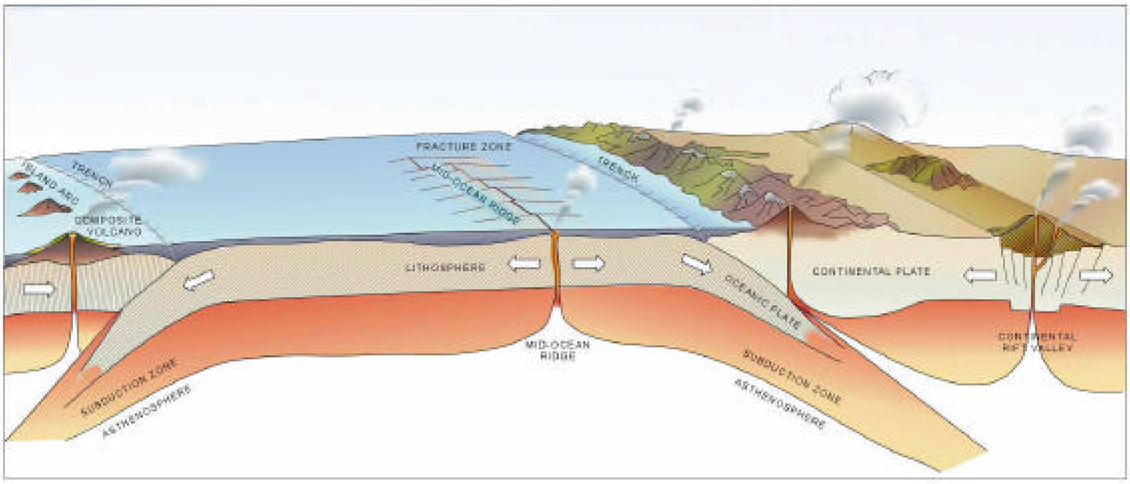

Figure 2
Schematic cross-section showing plate tectonic processes.

Spreading ridges, transform faults and subduction zones form a vast network that divides our planet into six immense and several other smaller lithospheric areas or *plates* (Figure 3). Because of the huge tensions generated by the Earth's thermal engine and the asymmetry of the zones producing and consuming lithospheric material, these plates drift slowly up against one another, shifting position continually. The margins of the plates correspond to weak, densely fractured zones of the crust, characterized by an intense seismicity, by a large number of volcanoes and, because of the ascent of very hot materials towards the surface, by a high terrestrial heat flow. As shown in Figure 3, the most important geothermal areas are located around plate margins.

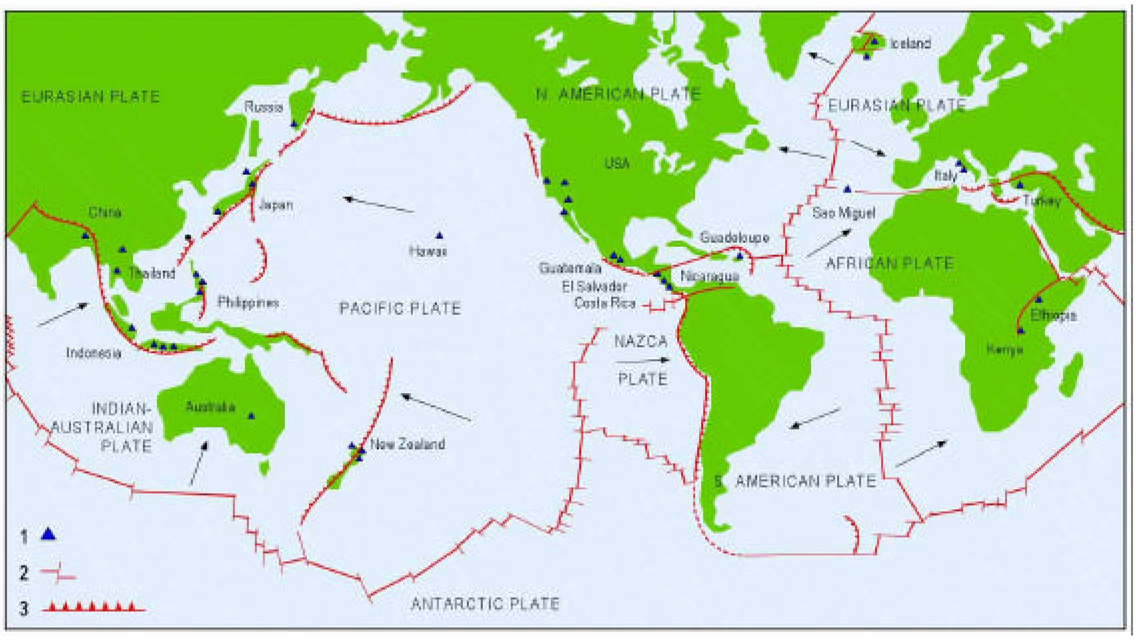

Figure 3
World pattern of plates, oceanic ridges, oceanic trenches, subduction zones, and geothermal fields. Arrows show the direction of movement of the plates towards the subduction zones. (1) Geothermal fields producing electricity; (2) mid-oceanic ridges crossed by transform faults (long transversal fractures); (3) subduction zones, where the subducting plate bends downwards and melts in the asthenosphere.

Geothermal systems

Geothermal systems can therefore be found in regions with a normal or slightly above normal geothermal gradient, and especially in regions around plate margins where the geothermal gradients may be significantly higher than the average value. In the first case the systems will be characterized by low temperatures, usually no higher than 100 °C at economic depths; in the second case the temperatures could cover a wide range from low to very high, and even above 400 °C.

What is a *geothermal system* and what happens in such a system? It can be described schematically as "convecting water in the upper crust of the Earth, which, in a confined space, transfers heat from a heat source to a heat sink, usually the free surface" (Hochstein, 1990). A geothermal system is made up of three main elements: a *heat source*, a *reservoir* and a *fluid* , which is the carrier that transfers the heat. The heat source can be either a very high temperature (> 600 °C) magmatic intrusion that has reached relatively shallow depths (5-10 km) or, as in certain low temperature systems, the Earth's normal temperature, which, as we explained earlier, increases with depth. The reservoir is a volume of hot permeable rocks from which the circulating fluids extract heat. The reservoir is generally overlain by a cover of impermeable rocks and connected to a surficial recharge area through which the meteoric waters can replace or partly replace the fluids that escape from the reservoir by natural means (through springs, for example) or are extracted by boreholes. The geothermal fluid is water, in the majority of cases meteoric water, in the liquid or vapour phase, depending on its temperature and pressure. This water often carries with it chemicals and gases such as CO_2, H_2S, etc. Figure 4 is a simple representation of an ideal geothermal system.

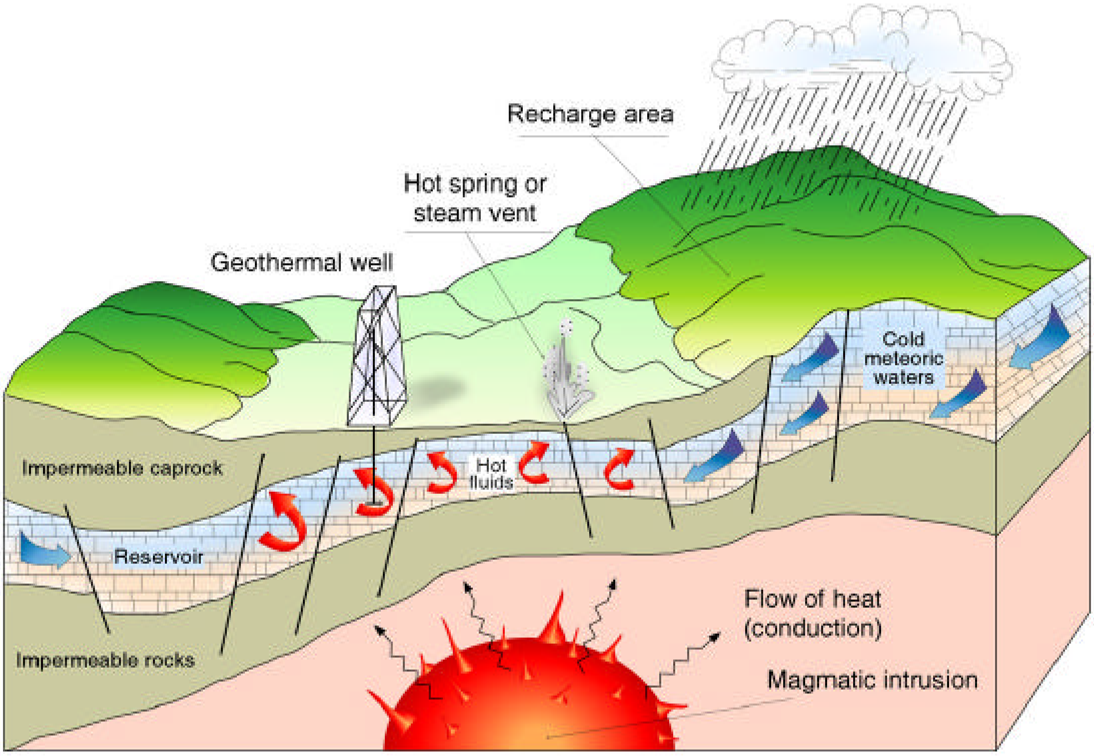

Figure 4
Schematic representation of an ideal geothermal system.

The mechanism underlying geothermal systems is by and large governed by *fluid convection*. Figure 5 describes schematically the mechanism in the case of an intermediate temperature hydrothermal system. Convection occurs because of the heating and consequent thermal expansion of fluids in a gravity field; heat, which is supplied at the base of the circulation system, is the energy that drives the system. Heated fluid of lower density tends to rise and to be replaced by colder fluid of high density, coming from the margins of the system. Convection, by its nature, tends to increase temperatures in the upper part of a system as temperatures in the lower part decrease (White, 1973).

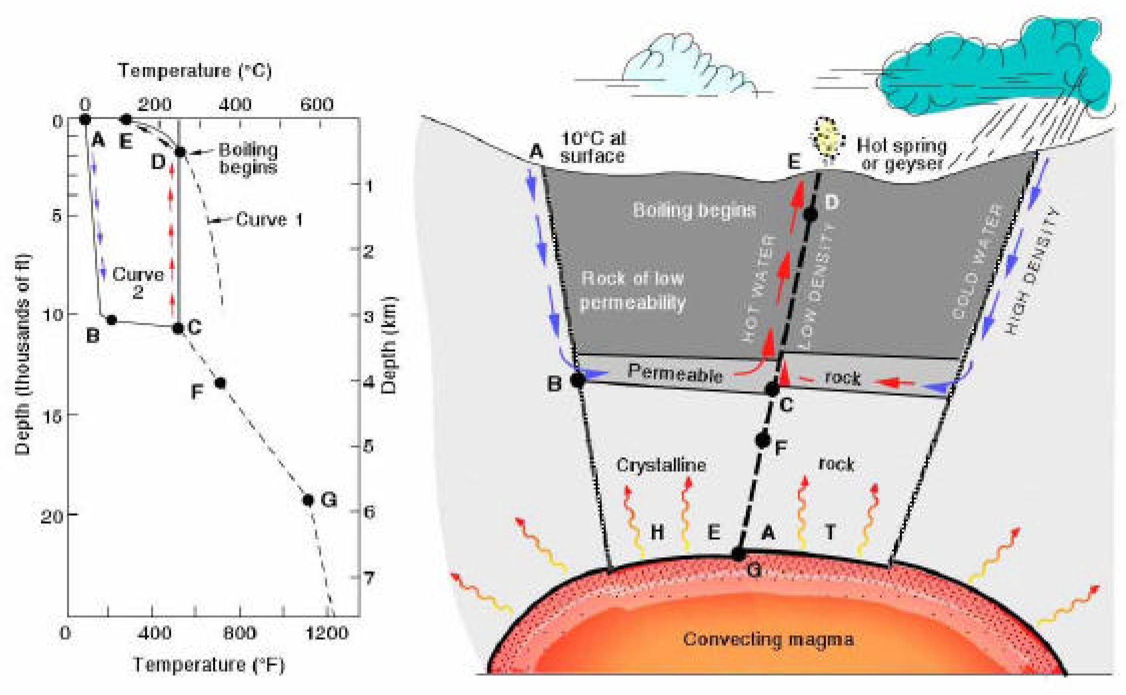

Figure 5
Model of a geothermal system. Curve 1 is the reference curve for the boiling point of pure water. Curve 2 shows the temperature profile along a typical circulation route from recharge at point A to discharge at point E. (From White,1973).

The phenomenon we have just described may seem quite a simple one but the reconstruction of a good model of a real geothermal system is by no means easy to achieve. It requires skill in many disciplines and a vast experience, especially when dealing with high temperature systems. Geothermal systems also occur in nature in a variety of combinations of geological, physical and chemical characteristics, thus giving rise to several different types of system.

Of all the elements of a geothermal system, the heat source is the only one that need be natural. Providing conditions are favourable, the other two elements could be "artificial". For example, the geothermal fluids extracted from the reservoir to drive the turbine in a geothermal power-plant could, after their utilization, be injected back into the reservoir through specific *injection wells*. In this way the natural recharge of the reservoir is integrated by an artificial recharge. For many years now re-injection has been adopted in various parts of the world as a means of drastically reducing the impact on the environment of power-plant operations. In the *Hot Dry Rock* (HDR) Project, implemented in the USA in the early 1970s, both the fluid and the reservoir are artificial (Garnish, 1987). High-pressured water is pumped through a specially drilled well into a deep body of hot, compact rock, causing its *hydraulic fracturing*. The water permeates these artificial fractures, extracting heat from the surrounding rock, which acts as a natural reservoir. This 'reservoir' is later penetrated by a second well, which is used to extract the heated water. The system therefore consists of (i) the borehole used for hydraulic fracturing, through which cold water is injected into (ii) the artificial reservoir, and (iii) the borehole used to extract the hot water. The entire system, complete with surface utilization plant, could form a closed loop. This interesting project was eventually abandoned after a number of years of experiments as it proved too expensive and the results were not entirely satisfactory.

For the last few years a great deal of effort has instead been invested in *'reservoir stimulation'* tests, which utilize some of the technology of the Hot Dry Rock project. Reservoir stimulation is based on the premise that hot rock formations containing fluids may often have such low permeabilities that the fluids are unable to circulate and no geothermal system can develop. This situation may simply be a consequence of the nature of the rock formation, but could also result from the partial sealing of existing fractures within or on the margins of exploited geothermal fields, as a consequence of mineral deposition during exploitation. Under certain conditions, the natural permeability of the rock can be increased, or its original permeability reinstated, by means of a technique developed in the oil industry whereby acid solutions are injected underground. Tests conducted so far have, however, indicated that the most effective means of stimulating the reservoir is by hydraulic fracturing.

DEFINITION AND CLASSIFICATION OF GEOTHERMAL RESOURCES

The following are some of the most common definitions and classifications of geothermal resources.

The most common criterion for classifying geothermal resources is that based on the enthalpy of the geothermal fluids that act as the carrier transporting heat from the deep hot rocks to the surface. *Enthalpy*, which can be considered more or less proportional to temperature, is used to express the heat (thermal energy) content of the fluids, and gives a rough idea of their 'value'. The resources are divided into low, medium and high enthalpy (or temperature) resources, according to several criteria (Table 4). Muffler and Cataldi (1978) use classification (a) of Table 4. Other experts prefer classification (b), such as Hochstein (1990), or (c), for example, Benderitter and Cormy (1990). Nicholson (1993) recommends classification (d), which makes a rough distinction between resources suited to electricity generation (high enthalpy) and resources more suited to direct heat use (low enthalpy). To avoid confusion and ambiguity the temperature values or ranges involved need specifying each time, since terms such as low, intermediate and high are meaningless at best, and frequently misleading.

Frequently a distinction is made between water- or liquid-dominated geothermal systems and vapour-dominated (or dry steam) geothermal systems (White, 1973). In *water-dominated systems* liquid water is the continuous, pressure-controlling fluid phase. Some vapour may be present, generally as discrete bubbles. These geothermal systems, whose temperatures may range from < 125 to > 225°C, are the most widely distributed in the world.

Depending on temperature and pressure conditions, they can produce hot water, water and steam mixtures, wet steam and, in some cases, dry steam. In *vapour-dominated systems* liquid water and vapour normally co-exist in the reservoir, with vapour as the continuous, pressure-controlling phase. Geothermal systems of this type, the best-known of which are Larderello in Italy and The Geysers in California, are somewhat rare, and are high-temperature systems. They normally produce dry-to- superheated steam.

The terms *wet*, *dry* and *superheated steam*, which are used frequently by geothermists, need some explanation for non-engineering readers. To make it as simple as possible, let us take the example of a pot filled with liquid water in which pressure can be kept constant at 1 atm (101.3 kPa). If we then heat the water, it will begin boiling once it reaches a temperature of 100°C (boiling temperature at a pressure of 1 atm) and will pass from the liquid to the gas (vapour) phase. After a certain time the pot will contain both liquid and vapour. The vapour coexisting with the liquid, and in thermodynamic equilibrium with it, is wet steam. If we continue to heat the pot and maintain the pressure at 1 atm, the liquid will evaporate entirely and the pot will contain steam only. This is what we call dry steam. Both wet and dry steam are called saturated steam. Finally, increasing the temperature to, say, 120°C, and keeping the pressure at 1 atm, we will obtain superheated steam with a superheating of 20°C, i.e. 20°C above the vaporization temperature at that pressure. At other temperatures and pressures, of course, these phenomena also take place in the underground, in what one author many years ago called "nature's tea-kettle".

Another division between geothermal systems is that based on the *reservoir equilibrium state* (Nicholson, 1993), considering the circulation of the reservoir fluid and the mechanism of heat transfer. In the *dynamic systems* the reservoir is continually recharged by water that is heated and then discharged from the reservoir either to the surface or into underground permeable formations. Heat is transferred through the system by convection and circulation of the fluid. This category includes high-temperature (>150°C) and low-temperature (<150°C) systems. In the *static systems* (also known as stagnant or storage systems) there is only minor or no recharge to the reservoir and heat is transferred only by conduction. This category includes low-temperature and geopressured systems. The *geopressured systems* are characteristically found in large sedimentary basins (e.g. Gulf of Mexico, USA) at depths of 3 - 7 km. The geopressured reservoirs consist of permeable sedimentary rocks, included within impermeable low-conductivity strata, containing pressurized hot water that remained trapped at the moment of deposition of the sediments. The hot water pressure approaches lithostatic pressure, greatly exceeding the hydrostatic pressure. The geopressured reservoirs can also contain significant amounts of methane. The geopressured systems could produce thermal and hydraulic energy (pressurized hot water) and methane gas. These resources have been investigated extensively, but so far there has been no industrial exploitation.

The term *geothermal field* is generally used to indicate an area with one or more geothermal systems, whether or not they are actually being exploited.

Geothermal energy is usually classified as *renewable* and *sustainable*. Renewable describes a property of the energy source, whereas sustainable describes how the resource is utilized.

The most critical aspect for the classification of geothermal energy as a renewable energy source is the rate of energy recharge. In the exploitation of natural geothermal systems, the recharge of energy takes place by advection of thermal water on the same time scale as production from the resource. This justifies our classification of geothermal energy as a renewable energy resource. In the case of hot, dry rocks, and some of the hot water aquifers in sedimentary basins, energy recharge is only by thermal conduction; due to the slowness of the latter process, however, hot dry rocks and some sedimentary reservoirs should be considered as finite energy resources (Stefansson, 2000).

The *sustainability in consumption* of a resource is dependent on its initial quantity, its rate of generation and its rate of consumption. Consumption can obviously be sustained over any time period in which a resource is being created faster than it is being depleted. The term *sustainable development* is used by the World Commission on Environment and Development to mean development that "..meets the needs of the present generation without compromising the needs of future generations." In this context, sustainable development does not imply that any given energy resource needs to be used in a totally sustainable fashion, but merely that a replacement for the resource can be found that will allow future generations to provide for themselves despite the fact that the particular resource has been depleted. Thus, it may not be necessary that a specific geothermal field be exploited in sustainable fashion. Perhaps we should direct our geothermal sustainability studies towards reaching and then sustaining a certain overall level of geothermal production at a national or regional level, both for electrical power generation and direct heat applications, for a certain period, say 300 years, by bringing new geothermal systems on line as others are depleted (Wright, 1998).

EXPLORATION

Objectives of exploration

The objectives of *geothermal exploration* are (Lumb, 1981):

1. To identify geothermal phenomena.
2. To ascertain that a useful geothermal production field exists.
3. To estimate the size of the resource.
4. To determine the type of geothermal field.
5. To locate productive zones.
6. To determine the heat content of the fluids that will be discharged by the wells in the geothermal field.
7. To compile a body of basic data against which the results of future monitoring can be viewed.
8. To determine the pre-exploitation values of environmentally sensitive parameters.
9. To acquire knowledge of any characteristics that might cause problems during field development.

Exploration methods

Geological and hydrogeological studies are the starting point of any exploration programme, and their basic function is that of identifying the location and extension of the areas worth investigating in greater detail and of recommending the most suitable exploration methods for these areas. Geological and hydrogeological studies have an important role in all subsequent phases of geothermal research, right up to the siting of exploratory and producing boreholes. They also provide the background information for interpreting the data obtained with the other exploration methods and, finally, for constructing a realistic model of the geothermal system and assessing the potential of the resource. The information obtained from the geological and hydrogeological studies may also be used in the production phase, providing valuable information for the reservoir and production engineers. The duration and cost of exploration can be appreciably reduced if an experienced geothermal geologist co-ordinates the exploration programme.

Geochemical surveys (including isotope geochemistry) are a useful means of determining whether the geothermal system is water- or vapour-dominated, of estimating the minimum temperature expected at depth, of estimating the homogeneity of the water supply, of inferring the chemical characteristics of the deep fluid and of determining the source of recharge water (Combs and Muffler, 1973). Valuable information can also be obtained on what problems are likely to arise during the utilization phase (e.g. corrosion and scaling on pipes and plant installations, environmental impact) and on how to avoid or combat them. The geochemical survey consists of sampling and chemical and/or isotope analyses of the water and gas from geothermal manifestations (hot springs, fumaroles, etc.) or wells in the study area. As the geochemical survey provides useful data for planning exploration and its cost is relatively low compared to other more sophisticated methods, such as the geophysical surveys, the geochemical techniques should be utilized as much as possible before proceeding with other more expensive methodologies.

Geophysical surveys are directed at obtaining indirectly, from the surface or from depth intervals close to the surface, the physical parameters of deep geological formations. These physical parameters include temperature (thermal survey), electrical conductivity (electrical and electromagnetic methods), propagation velocity of elastic waves (seismic survey), density (gravity survey) and magnetic susceptibility (magnetic survey). Some of these techniques, such as seismics, gravity and magnetics, which are traditionally adopted in oil research, can give valuable information on the shape, size, depth and other important characteristics of the deep geological structures that could constitute a geothermal reservoir, but they give little or no indication as to whether these structures actually contain the fluids that are the primary objective of research. These methodologies are, therefore, more suited to defining details during the final stages of exploration, before the exploratory wells are sited. Information on the existence of geothermal fluids in the geological structures can be obtained with the electrical and electromagnetic prospectings, which are more sensitive than the other surveys to the presence of these fluids and to variations in temperature; these two techniques have been applied widely with satisfactory results. The magnetotelluric method, in particular, has been greatly improved over the last few years, and now offers a vast spectrum of possible applications, despite the fact that it requires sophisticated instrumentation and is sensitive to background noise in urbanized areas. The main advantage of the magnetotelluric method is that it can be used to define deeper structures than are attainable with the electric and the other electro-magnetic techniques. The thermal techniques (temperature measurements, determination of geothermal gradient and terrestrial heat flow) can often provide a good approximation of the temperature at the top of the reservoir.

Drilling of *exploratory wells* represents the final phase of any geothermal exploration programme and is the only means of determining the real characteristics of the geothermal reservoir and thus of assessing its potential (Combs and Muffler, 1973). The data provided by exploratory wells should be capable of verifying all the hypotheses and models elaborated from the results of surface exploration and of confirming that the reservoir is productive and that it contains enough fluids of adequate characteristics for the utilization for which it is intended. Siting of the exploratory wells is therefore a very delicate operation.

Exploration programme

Before drawing up a geothermal exploration programme all existing geological, geophysical and geochemical data must be collected and integrated with any data available from previous studies on water, minerals and oil resources in the study area and adjacent areas. This information frequently plays an important role in defining the objectives of the geothermal exploration programme and could lead to a significant reduction in costs.

The exploration programme is usually developed on a step-by-step basis: *reconnaissance*, *pre-feasibility* and *feasibility*. During each of these phases we gradually eliminate the less interesting areas and concentrate on the most promising ones. The methods used also become progressively more sophisticated and more detailed as the programme develops. The size and budget of the entire programme should be proportional to its objectives, to the importance of the resources we expect to find, and to the planned forms of utilization. The programme schedule should be flexible and reassessed as the results come in from the various surveys of each phase; similarly the geological-geothermal model should be progressively updated and improved. These periodic re-assessments of the programme should ideally eliminate any operations that are no longer necessary and insert others, according to the results attained at each stage. Clearly any reduction in the number and size of the prospectings will lead to a decrease in costs, and also a corresponding increase in the risk of error or failure. Conversely, by decreasing the risk of error we increase the overall cost. The economic success of a geothermal exploration programme hinges on finding the proper balance between the two.

UTILIZATION OF GEOTHERMAL RESOURCES

Electricity generation is the most important form of utilization of high-temperature geothermal resources (> 150°C). The medium-to-low temperature resources (< 150°C) are suited to many different types of application. The classical Lindal diagram (Lindal, 1973) (Figure 6), which shows the possible uses of geothermal fluids at different temperatures, still holds valid, but the generation of electric energy in binary cycle plants can now be added above 85°C. The lower limit of 20°C is exceeded only in very particular conditions, or by the use of heat pumps. The Lindal diagram emphasizes two important aspects of the utilization of geothermal resources (Gudmundsson, 1988): (a) with cascading and combined uses it is possible to enhance the feasibility of geothermal projects and (b) the resource temperature may limit the possible uses. Existing designs for thermal processes can, however, be modified for geothermal fluid utilization in certain cases, thus widening its field of application .

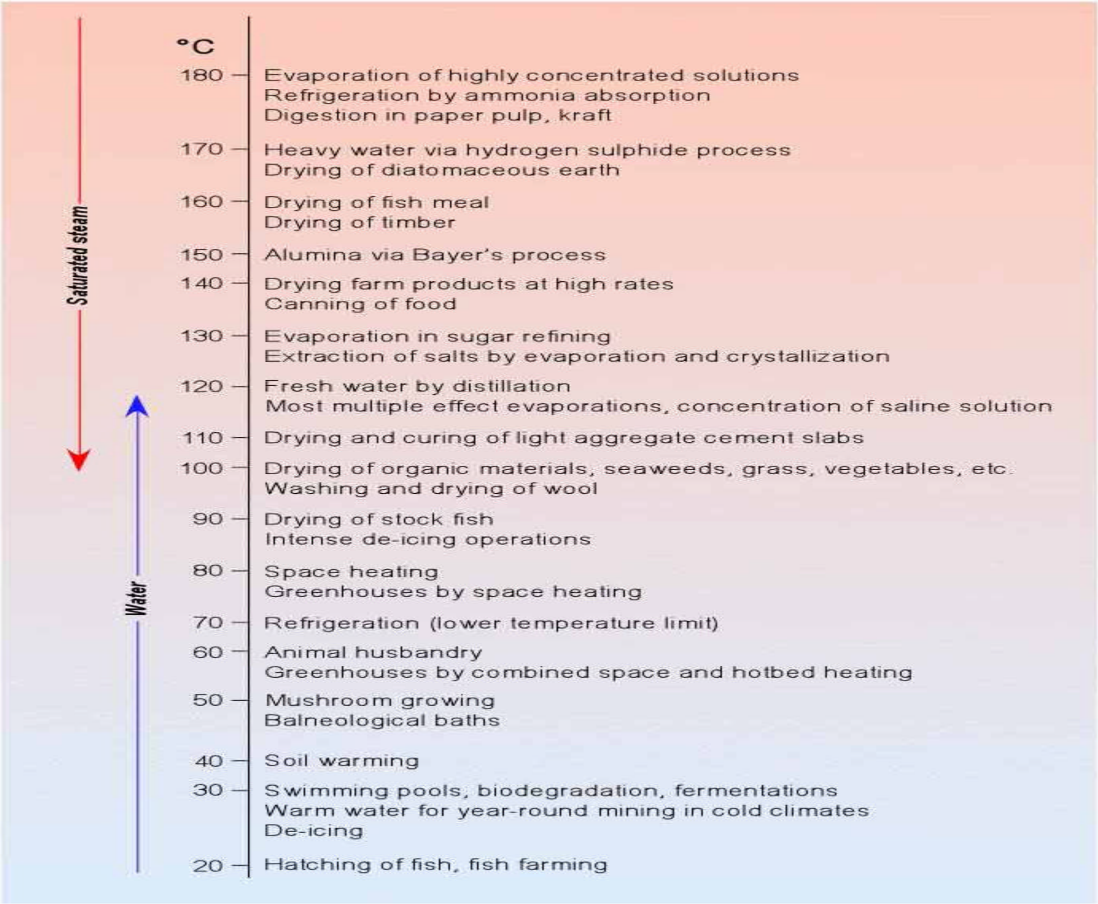

Figure 6
The Lindal diagram (Lindal, 1973).

Electricity generation

Electricity generation mainly takes place in conventional steam turbines and binary plants, depending on the characteristics of the geothermal resource.

Conventional steam turbines require fluids at temperatures of at least 150 °C and are available with either atmospheric (backpressure) or condensing exhausts. Atmospheric exhaust turbines are simpler and cheaper. The steam, direct from dry steam wells or, after separation, from wet wells, is passed through a turbine and exhausted to the atmosphere. With this type of unit, steam consumption (from the same inlet pressure) per kilowatt-hour produced is almost double that of a condensing unit. However, the atmospheric exhaust turbines are extremely useful as pilot plants, stand-by plants, in the case of small supplies from isolated wells, and for generating electricity from test wells during field development. They are also used when the steam has a high noncondensable gas content (> 12% in weight). The atmospheric exhaust units can be constructed and installed very quickly and put into operation in little more than 13-14 months from their order date. This type of machine is usually available in small sizes (2.5 - 5 MW_e).

The condensing units, having more auxiliary equipment, are more complex than the atmospheric exhaust units and the bigger sizes take up to twice as long to construct and install. The specific steam consumption of the condensing units is, however, about half that of the atmospheric exhaust units. Condensing plants of 55 - 60 MW_e capacity are very common, but recently plants of 110 MW_e have also been constructed and installed.

Generating electricity from low-to-medium temperature geothermal fluids and from the waste hot waters coming from the separators in water - dominated geothermal fields has made considerable progress since improvements were made in binary fluid technology. The *binary plants* utilize a secondary working fluid, usually an organic fluid, that has a low boiling point and high vapour pressure at low temperatures when compared to steam. The secondary fluid is operated through a conventional Rankine cycle: the geothermal fluid yields heat to the secondary fluid through heat exchangers, in which this fluid is heated and vaporizes; the vapour produced drives a normal axial flow turbine, is then cooled and condensed, and the cycle begins again. By selecting suitable secondary fluids, binary systems can be designed to utilize geothermal fluids in the temperature range 85-175°C. The upper limit depends on the thermal stability of the organic binary fluid, and the lower limit on technical-economic factors: below this temperature the size of the heat exchangers required would render the project uneconomical. Apart from low-to-medium temperature geothermal fluids and waste fluids, binary systems can also be utilized where flashing of the geothermal fluids should preferably be avoided (for example, to prevent well sealing). In this case, downhole pumps can be used to keep the fluids in a pressurized liquid state, and the energy can be extracted from the circulating fluid by means of binary units.

Binary plants are usually constructed in small modular units of a few hundred kW_e to a few MW_e capacity. These units can then be linked up to create power-plants of a few tens of megawatts. Their cost depends on a number of factors, but particularly on the temperature of the geothermal fluid produced, which influences the size of the turbine, heat exchangers and cooling system. The total size of the plant has little effect on the specific cost, as a series of standard modular units is joined together to obtain larger capacities.

After long trial and error, binary plant technology is emerging as a very cost-effective and reliable means of converting into electricity the energy available from water-dominated geothermal fields (below 175 °C) (ORMAT, 1989). A new binary cycle system has been developed recently, called the Kalina cycle. The Kalina cycle uses an ammonia-water mixture as the working fluid and takes advantage of regenerative heating. The ammonia-water mixture has a low boiling point, so that the excess heat coming from the turbine's exhaust can be used to vaporize a substantial portion of the working fluid. This plant is estimated to be up to 40% more efficient than existing geothermal binary power plants.

Direct heat uses

Direct heat use is one of the oldest, most versatile and also the most common form of utilization of geothermal energy. Space and district heating, agricultural applications, aquaculture and industrial uses are the best known and most widespread forms of utilization, but other forms are already in use or in the late planning stages.

Space and district heating have made great progress in Iceland, where the total capacity of the operating geothermal district heating system had risen to about 1200 MW_t by the end of 1999 (Figure 7), but they are also widely distributed in the East European countries, as well as in the United States, China, Japan, France, etc.

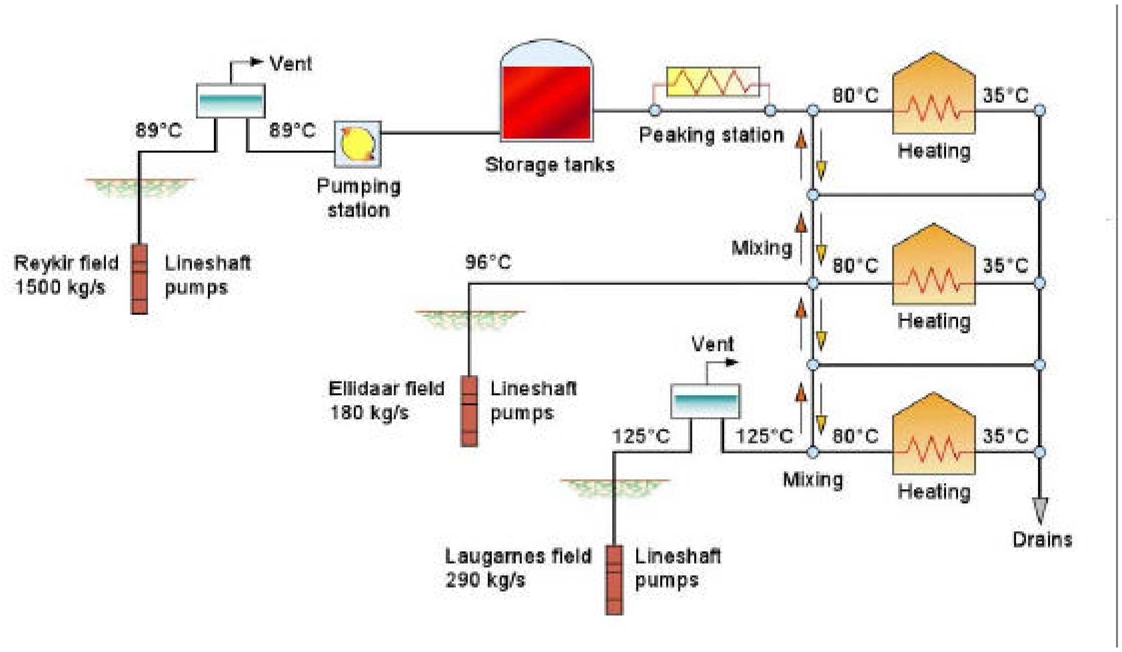

Figure 7

Simplified flow diagram of the geothermal district heating system of Reykjavik. (From Gudmundsson, 1988)

Geothermal district heating systems are capital intensive. The main costs are initial investment costs , for production and injection wells, downhole and transmission pumps, pipelines and distribution networks, monitoring and control equipment, peaking stations and storage tanks. Operating expenses, however, are comparatively lower than in conventional systems, and consist of pumping power, system maintenance, control and management. A crucial factor in estimating the initial cost of the system is the thermal load density, or the heat demand divided by the ground area of the district. A high heat density determines the economic feasibility of a district heating project, since the distribution network is expensive. Some economic benefit can be achieved by combining heating and cooling in areas where the climate permits. The load factor in a system with combined heating and cooling would be higher than the factor for heating alone, and the unit energy price would consequently improve (Gudmundsson, 1988).

Space cooling is a feasible option where absorption machines can be adapted to geothermal use. The technology of these machines is well known, and they are readily available on the market. The absorption cycle is a process that utilizes heat instead of electricity as the energy source. The refrigeration effect is obtained by utilizing two fluids: a refrigerant, which circulates, evaporates and condenses, and a secondary fluid or absorbent. For applications above 0 °C (primarily in space and process conditioning), the cycle uses lithium bromide as the absorbent and water as the refrigerant. For applications below 0 °C an ammonia/water cycle is adopted, with ammonia as the refrigerant and water as the absorbent. Geothermal fluids provide the thermal energy to drive these machines, although their efficiency decreases with temperatures lower than 105 °C.

Geothermal *space conditioning* (heating and cooling) has expanded considerably since the 1980s, following on the introduction and widespread use of *heat pumps*. The various systems of heat pumps available permit us to economically extract and utilize the heat content of low-temperature bodies, such as the ground and shallow aquifers, ponds, etc. (see, for example, Figure 8). As our engineering readers will already know, heat pumps are machines that move heat in a direction opposite to that in which it would tend to go naturally, i.e. from a cold space or body to a warmer one. A heat pump is effectively nothing more than a refrigeration unit (Rafferty, 1997). Any refrigeration device (window air conditioner, refrigerator, freezer, etc.) moves heat from a space (to keep it cool) and discharges that heat at higher temperatures. The only difference between a heat pump and a refrigeration unit is the desired effect, cooling for the refrigeration unit and heating for the heat pump. A second distinguishing factor of many heat pumps is that they are reversible and can provide either heating or cooling in the space. Heat pumps need electricity to operate, but in suitable climatic conditions and with a good design, the energy balance is a positive one. Ground-coupled and ground-water heat pump systems are being installed in great numbers in the United States, Switzerland and Germany. Aquifers and soils at temperatures in the 5 to 30 °C range are being used in these systems (Lund, 1996).

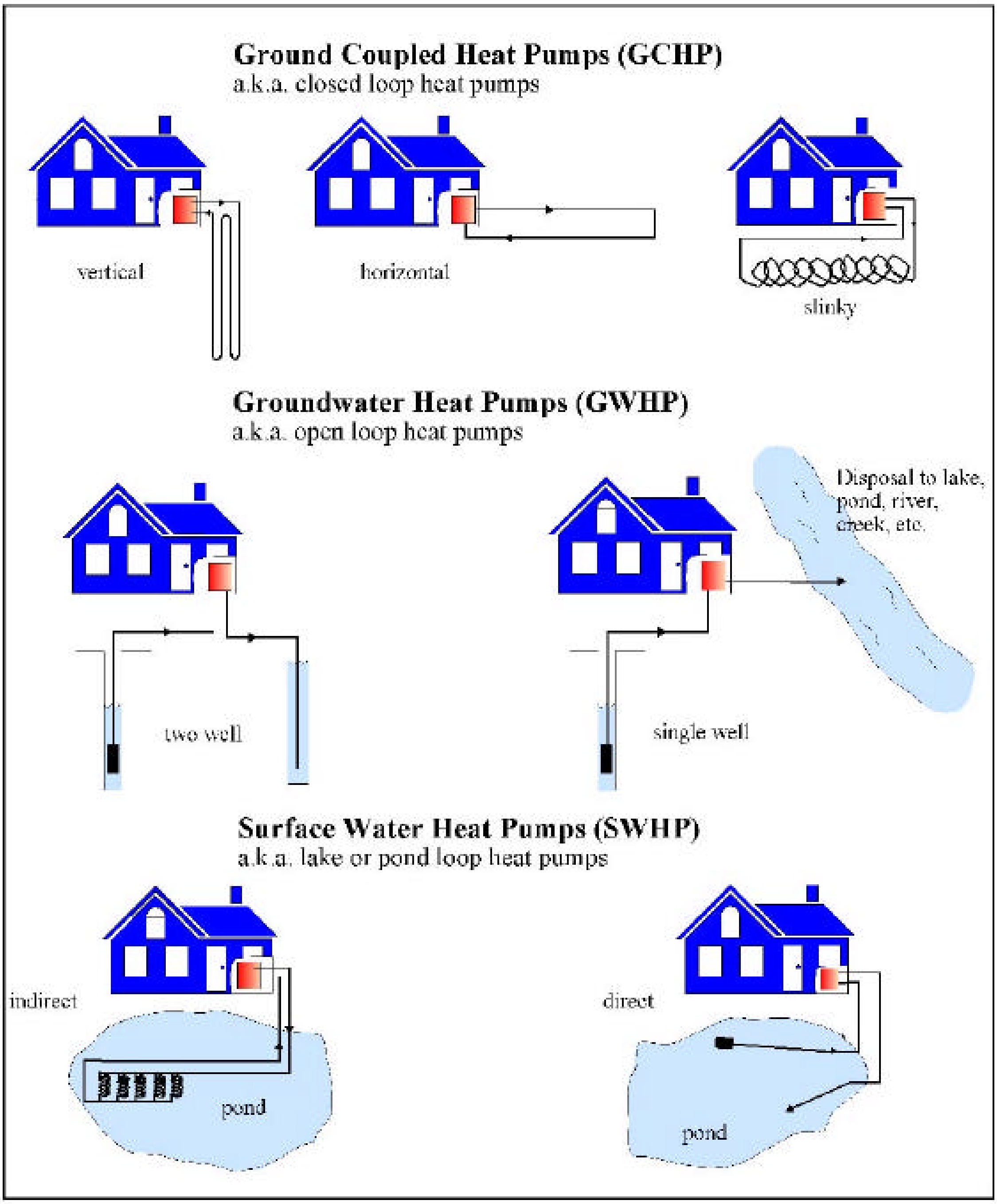

Figure 8
Simplified schemes of ground source heat pumps.

The *agricultural applications* of geothermal fluids consist of open-field agriculture and greenhouse heating. Thermal water can be used in open-field agriculture to irrigate and/or heat the soil. The greatest drawback in irrigating with warm waters is that, to obtain any worthwhile variation in soil temperature, such large quantities of water are required at temperatures low enough to prevent damage to the plants that the fields would be flooded. One possible solution to this problem is to adopt a subsurface irrigation system coupled to a buried pipeline soil heating device. Heating the soil in buried pipelines without the irrigation system could decrease the heat conductivity of the soil because of the drop in humidity around the pipes and consequent thermal insulation. The best solution seems to be that of combining soil heating and irrigation. The chemical composition of the geothermal waters used in irrigation must be monitored carefully to avoid adverse effects on the plants. The main advantages of temperature control in open-field agriculture are: (a) it prevents any damage ensuing from low environmental temperatures, (b) it extends the growing season, increases plant growth, and boosts production, and (c) it sterilizes the soil (Barbier and Fanelli, 1977).

The most common application of geothermal energy in agriculture is, however, in *greenhouse heating*, which has been developed on a large scale in many countries. The cultivation of vegetables and flowers out-of-season, or in an unnatural climate, can now draw on a widely experimented technology. Various solutions are available for achieving optimum growth conditions, based on the optimum growth temperature of each plant (Figure 9), and on the quantity of light, on the CO_2 concentration in the greenhouse environment, on the humidity of the soil and air, and on air movement. The walls of the greenhouse can be made of glass, fibreglass, rigid plastic panels or plastic film. Glass panels are more transparent than plastic and will let in far more light, but will provide less thermal insulation, are less resistant to shocks, and are heavier and more expensive than the plastic panels. The simplest greenhouses are made of single plastic films, but recently some greenhouses have been constructed with a double layer of film separated by an air space. This system reduces the heat loss through the walls by 30 - 40%, and thus greatly enhances the overall efficiency of the greenhouse. Greenhouse heating can be accomplished by forced circulation of air in heat exchangers, hot-water circulating pipes or ducts located in or on the floor, finned units located along the walls and under benches, or a combination of these methods. Exploitation of geothermal heat in greenhouse heating can considerably reduce their operating costs, which in some cases account for 35% of the product costs (vegetables, flowers, house-plants and tree seedlings).

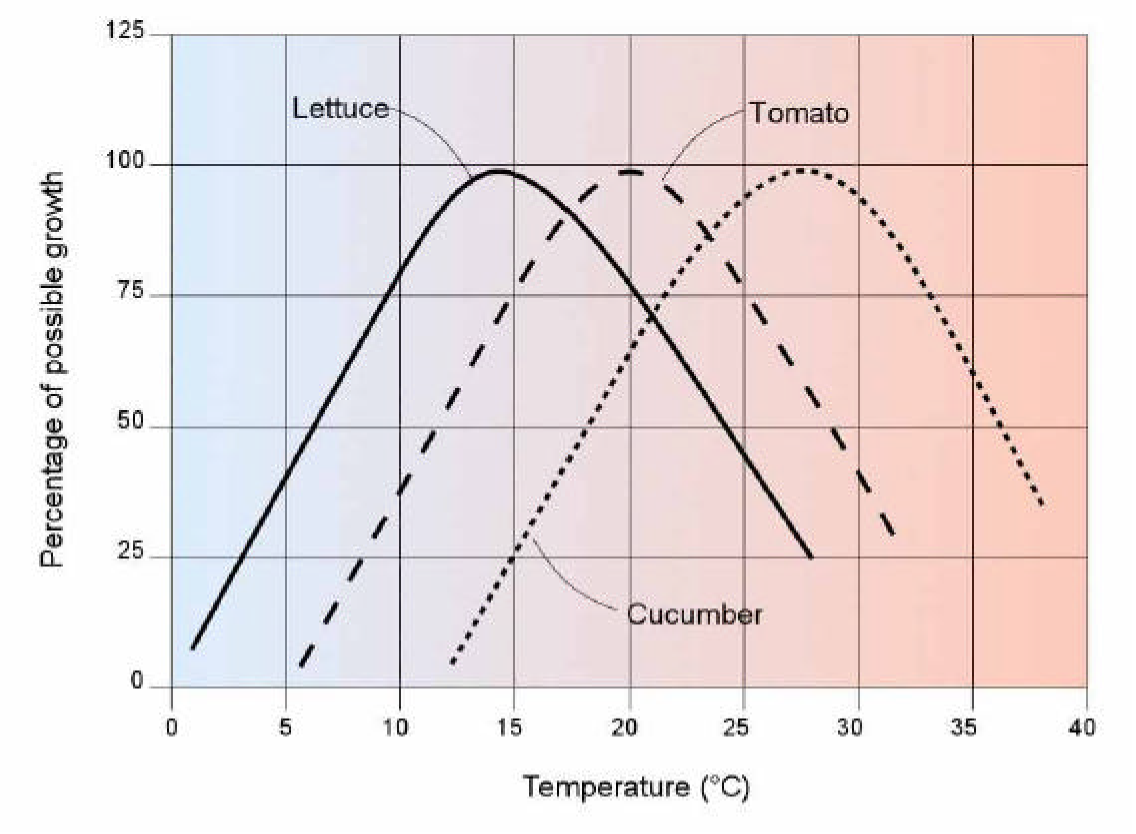

Figure 9
Growth curves for some crops. (From Beall and Samuels, 1971).

Farm animals and aquatic species, as well as vegetables and plants, can benefit in quality and quantity from optimum conditioning of their environmental temperature (Figure 10). In many cases geothermal waters could be used profitably in a combination of *animal husbandry* and geothermal greenhouses. The energy required to heat a breeding installation is about 50% of that required for a greenhouse of the same surface area, so a cascade utilization could be adopted. Breeding in a temperature-controlled environment improves animal health, and the hot fluids can also be utilized to clean, sanitize and dry the animal shelters and waste products (Barbier and Fanelli, 1977).

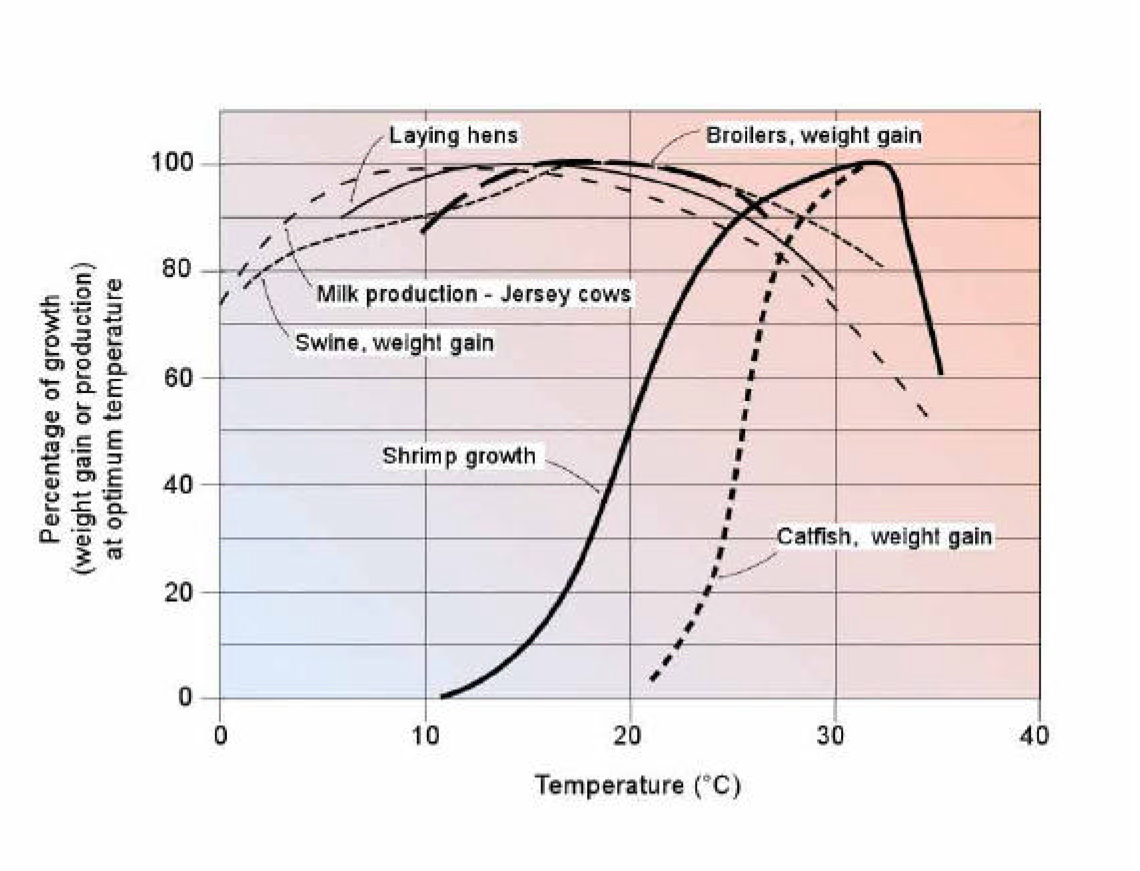

Figure 10
Effect of temperature on growth or production of food animals. (From Beall and Samuels, 1971).

Aquaculture , which is the controlled breeding of aquatic forms of life, is gaining world-wide importance nowadays, due to an increasing market demand. Control of the breeding temperatures for aquatic species is of much greater importance than for land species, as can be seen in Figure 10, which shows that the growth curve trend of aquatic species is very different from that of land species. By maintaining an optimum temperature artificially we can breed more exotic species, improve production and even, in some cases, double the reproductive cycle (Barbier and Fanelli, 1977). The species that are typically raised are carp, catfish, bass, tilapia, mullet, eels, salmon, sturgeon, shrimp, lobster, crayfish, crabs, oysters, clams, scallops, mussels and abalone.

Aquaculture also includes alligator and crocodile breeding, which could prove an innovative and lucrative industry. Experiments in the United States have shown that, by maintaining its growth temperature at about 30 °C, an alligator can be grown to a length of about 2 m in 3 years, whereas alligators bred under natural conditions will reach a length of only 1.2 m over the same period.

Another form of aquaculture is the cultivation of protein-rich microalgae, such as *Spirulina*.

The temperatures required for several aquatic species are generally in the 20—30 °C range. The size of the installation will depend on the temperature of the geothermal source, the temperature required in the fish ponds and the heat losses from the latter.

The entire temperature range of geothermal fluids, whether steam or water, can be exploited for *industrial applications*, as shown in the Lindal diagram (Figure 6). The different possible forms of utilization include process heating, evaporation, drying, distillation, sterilization, washing, de-icing, salt and chemical extraction, as well as oil recovery. Industrial process heat has applications in 19 countries, where the installations tend to be large and energy consumption high. Examples include: concrete curing, bottling of water and carbonated drinks, paper and vehicle parts production, oil recovery, milk pasteurization, leather industry, chemical extraction, CO_2 extraction (Lund and Freeston, 2001), mushroom growing and laundry use, salt extraction and diatomaceous earth drying, pulp and paper processing, and borate and boric acid production.

ENVIRONMENTAL IMPACT

During the 1960s, when our environment was in a healthier state than it is at present and we were less aware of the threat to the earth, geothermal energy was still considered a 'clean energy'. There is actually no way of producing or transforming energy into a form that can be utilized by man without making some direct or indirect impact on the environment. Even the oldest and simplest form of producing thermal energy, burning wood, has a detrimental effect, and deforestation, one of the major problems in recent years, first began when our ancestors cut down trees to cook their food and heat their houses. Similarly, exploitation of geothermal energy also has an impact on the environment, although it must be said that it is one of the least polluting forms.

Sources of pollution

In most cases the degree to which geothermal exploitation affects the environment is proportional to the scale of such exploitation (Lunis and Breckenridge,1991). Table 5 summarizes the probability and relative severity of the effects on the environment of developing geothermal direct-use projects. Electricity generation in binary cycle plants will affect the environment in the same way as direct heat uses. The effects are potentially greater in the case of conventional back-pressure or condensing power-plants, especially as regards air quality, but can be kept within acceptable limits.

Any modification to our environment must be evaluated carefully, in deference to the relevant laws and regulations, which in some countries are very severe, but also because an apparently insignificant modification could trigger a chain of events whose impact is difficult to fully assess beforehand. For example, a mere 2-3 °C increase in the temperature of a body of water as a result of discharging the waste water from a utilization plant could damage its ecosystem. The plant and animal organisms that are most sensitive to temperature variations could gradually disappear, leaving a fish species without its food source. An increase in water temperature could impair development of the eggs of other fish species. If these fish are edible and provide the necessary support for a community of fishermen, then their disappearance could be critical for the community at large. The example we have just given is hypothetical but does not fall short of the truth.

The first perceptible effect on the environment is that of *drilling*, whether the boreholes are shallow ones for measuring the geothermal gradient in the pre-feasibility exploration phase, or exploratory/producing wells. Installation of a drilling rig and all the accessory equipment entails the construction of access roads and a drilling pad. The latter will cover an area ranging from 300—500 m^2 for a small truck-mounted rig (max.depth 300—700 m) to 1200—1500 m^2 for a small-to-medium rig (max. depth of 2000 m). These operations will modify the surface morphology of the area and could damage local plants and wildlife. Blowouts can pollute surface water; blowout preventers should be installed when drilling geothermal wells where high temperatures and pressures are anticipated (Lunis and Breckenridge,1991). During drilling or flowtests undesirable gases may be discharged into the atmosphere. The impact on the environment caused by drilling mostly ends once drilling is completed.

The next stage, installation of the pipelines that will transport the geothermal fluids and construction of the *utilization plants*, will also affect animal and plant life and the surface morphology. The scenic view will be modified, although in some areas such as Larderello, Italy, the network of pipelines criss-crossing the countryside and the power-plant cooling towers have become an integral part of the panorama and are indeed a famous tourist attraction.

Environmental problems also arise during plant operation. Geothermal fluids (steam or hot water) usually contain *gases* such as carbon dioxide (CO_2), hydrogen sulphide (H_2S), ammonia (NH_3), methane (CH_4), and trace amounts of other gases, as well as *dissolved substances* whose concentrations usually increase with temperature. For example, sodium chloride (NaCl), boron (B), arsenic (As) and mercury (Hg) are a source of pollution if discharged into the environment. Some geothermal fluids, such as those utilized for district-heating in Iceland, are freshwaters, but this is an exception to the rule. The waste waters from geothermal plants also have a higher temperature than the environment and therefore constitute a potential thermal pollutant.

Air pollution may become a problem when generating electricity in conventional power-plants. Hydrogen sulphide is one of the main pollutants. The odour threshold for hydrogen sulphide in air is about 5 parts per billion by volume and subtle physiological effects can be detected at slightly higher concentrations (Weres, 1984). Various processes, however, can be adopted to reduce emissions of this gas. Carbon dioxide is also present in the fluids used in the geothermal power plants, although much less CO_2 is discharged from these plants than from fossil-fuelled power stations: 13 – 380 g for every kWh of electricity produced in the geothermal plants, compared to the 1042 g/kWh of the coal-fired plants, 906 g/kWh of oilfired plants, and 453 g/kWh of natural gas-fired plants (Fridleifsson, 2001). Binary cycle plants for electricity generation and district-heating plants may also cause minor problems, which can virtually be overcome simply by adopting closed-loop systems that prevent gaseous emissions (Willard *et al.*, 1979).

Discharge of waste waters is also a potential source of chemical pollution. Spent geothermal fluids with high concentrations of chemicals such as boron, fluoride or arsenic should be treated, re-injected into the reservoir, or both. However, the low-to-moderate temperature geothermal fluids used in most direct-use applications generally contain low levels of chemicals and the discharge of spent geothermal fluids is seldom a major problem. Some of these fluids can often be discharged into surface waters after cooling (Lunis and Breckenridge,1991). The waters can be cooled in special storage ponds or tanks to avoid modifying the ecosystem of natural bodies of waters (rivers, lakes and even the sea).

Extraction of large quantities of fluids from geothermal reservoirs may give rise to *subsidence* phenomena, i.e. a gradual sinking of the land surface. This is an irreversible phenomenon, but by no means catastrophic, as it is a slow process distributed over vast areas. Over a number of years the lowering of the land surface could reach detectable levels, in some cases of the order of a few tens of centimetres and even metres, and should be monitored systematically, as it could damage the stability of the geothermal buildings and any private homes in the neighbourhood. In many cases subsidence can be prevented or reduced by re-injecting the geothermal waste waters.

The withdrawal and/or re-injection of geothermal fluids may trigger or increase the frequency of *seismic events* in certain areas. However these are microseismic events that can only be detected by means of instrumentation. Exploitation of geothermal resources is unlikely to trigger major seismic events, and so far has never been known to do so.

The *noise* associated with operating geothermal plants could be a problem where the plant in question generates electricity. During the production phase there is the higher pitched noise of steam travelling through pipelines and the occasional vent discharge. These are normally acceptable. At the power plant the main noise pollution comes from the cooling tower fans, the steam ejector, and the turbine 'hum' (Brown, 1995). The noise generated in direct heat applications is usually negligible.

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Table 1 Installed geothermal generating capacities world-wide (Huttrer, 2001, modified)

Country	1995 (MW_e)	2000 (MW_e)	1995-2000 increase in MW_e	% increase
Argentina	0.67	0	-0.67	n/a
Australia	0.17	0.17	0	0
China	28.78	29.17	0.39	1.35
Costa Rica	55	142.5	87.5	159
El Salvador	105	161	56	53.3
Ethiopia	0	8.52	8.52	infinite
France	4.2	4.2	0	0
Guatemala	0	33.4	33.4	infinite
Iceland	50	170	120	240
Indonesia	309.75	589.5	279.75	90.3
Italy	631.7	785	153.3	24.3
Japan	413.705	546.9	133.195	32.2
Kenya	45	45	0	0
Mexico	753	755	2	0.3
New Zealand	286	437	151	52.8
Nicaragua	70	70	0	0
Philippines	1 227	1 909	682	55.8
Portugal	5	16	11	220
Russia	11	23	12	109
Thailand	0.3	0.3	0	0
Turkey	20.4	20.4	0	0
USA	2 816.7	2 228	-588	n/a
Total	6 833	7 974	1 141	17

Table 2 Electric capacity from geothermal energy on total electric capacity for some developing countries in 1996 (MW_e)

Country	Total electric installed power	Geothermal electric installed power	% of the total power installed
Nicaragua	457	70	15.3
Philippines	8646	1200	13.9
El Salvador	980	105	10.7
Kenya	809	45	5.6
Costa Rica	1165	60	5.2
Indonesia	21 312	375	1.7
Mexico	44 258	755	1.7

Table 3. Non-electric uses of geothermal energy in the world (2000): installed thermal power (in MWt) and energy use (in TJ/yr). Taken from Lund and Freeston(2001).

Country	Power (MW_t)	Energy (TJ/yr)
Algeria	100	1586
Argentina	25.7	449
Armenia	1	15
Australia	34.4	351
Austria	255.3	1609
Belgium	3.9	107
Bulgaria	107.2	1637
Canada	377.6	1023
Caribbean Islands	0.1	1
Chile	0.4	7
China	2282	37908
Colombia	13.3	266
Croatia	113.9	555
Czech Republic	12.5	128
Denmark	7.4	75
Egypt	1	15
Finland	80.5	484
France	326	4895
Georgia	250	6307
Germany	397	1568
Greece	57.1	385
Guatemala	4.2	117
Honduras	0.7	17
Hungary	472.7	4086
Iceland	1469	20170
India	80	2517
Indonesia	2.3	43
Israel	63.3	1713
Italy	325.8	3774
Japan	1167	26933
Jordan	153.3	1540
Kenya	1.3	10
Korea	35.8	753
Lithuania	21	599
Macedonia	81.2	510
Mexico	164.2	3919
Nepal	1.1	22
Netherlands	10.8	57
New Zealand	307.9	7081
Norway	6	32
Peru	2.4	49
Philippines	1	25
Poland	68.5	275

Portugal	5.5	35
Romania	152.4	2871
Russia	308.2	6144
Serbia	80	2375
Slovak Republic	132.3	2118
Slovenia	42	705
Sweden	377	4128
Switzerland	547.3	2386
Thailand	0.7	15
Tunisia	23.1	201
Turkey	820	15756
United Kingdom	2.9	21
United States	3766	20302
Venezuela	0.7	14
Yemen	1	15
Total	15145	190699

Table 4 Classification of geothermal resources (°C)

	(a)	(b)	(c)	(d)
Low enthalpy resources	< 90	< 125	< 100	=150
Intermediate enthalpy resources	90-150	125 -225	100 -200	—
High enthalpy resources	> 150	> 225	> 200	> 150

Source: (a) Muffler and Cataldi (1978).
(b) Hochstein (1990).
(c) Benderitter and Cormy (1990).
(d) Nicholson (1993).

Table 5 Probability and severity of potential environmental impact of direct use projects

Impact	Probability of its occurring	Severity of consequences
Air quality pollution	L	M
Surface water pollution	M	M
Underground pollution	L	M
Land subsidence	L	L to M
High noise levels	H	L to M
Well blowouts	L	L to M
Conflicts with cultural and archeological features	L to M	M to H
Social-economic problems	L	L
Chemical or thermal pollution	L	M to H
Solid waste disposal	M	M to H

L = Low; M = Moderate; H = High

Source: Lunis and Breckenridge (1991)